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ORIGIN OF THE ZODIACAL LIGHT AND THE VARIATIONS OF ITS BRIGHTNESS

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ABSTRACT. It has been suggested that the zodiacal light originates from the scattering of photospheric radiation by electrons and interplanetary dust particles lying within an ellipsoidal volume in the interplanetary space with the sun at its centre. The corpuscles in the solar corpuscular stream, leaving the sun with velocities less than the velocity of escape and carrying the interplanetary dust particles with them, form the ellipsoidal volume with the rotation of the sun, and account for the lenticular shape of the zodiacal light and the varying inclinations of its light axis with the plane of the ecliptic in different seasons. The variations of the intensities during magnetic storms and with the advent of meteor swarms are satisfactorily explained with the help of the above picture, as due to the augmentations in the number of electrons in the solar corpuscular stream and the number of dust particles respectively.

I

According to the planetary theory (Mitra, 1952) of the zodiacal light, the phenomenon is manifested as a result of scattering of sunlight by a cloud of interplanetary dust particles of meteoric origin. The characteristic conical shape of the light is attributed to a concentration of the dust particles in the plane of the ecliptic in the form of a collossal lens having the sun at its centre. The particles are supposed to be rather small bodies but large enough not to be repelled by solar radiation pressure.

On the hypothesis that the outer corona of the sun is an extension of the zodiacal light and manifested in a similar manner, van de Hulst (1947) estimated the radii of the scattering particles to be of the order of .01 to 03 cm., and suggested a thickness of the order of 0.1 A.U. for the lenticular dust cloud. Allen (1946) from similar considerations, but assuming a non-homogeneous distribution of the dust particles, deduced the radii of the particles to be of the order of .001 cm. with density varying as r^{-1}, where r is the distance from the sun.

The observed polarization and brightness in the zodiacal light may be ascribed either to scattering by electrons or to reflection from interplanetary dust particles consisting of pulverized minerals like lava, basalt and granite, etc. (Whipple and Gossner, 1949). The first suggestion according to the estimates of Whipple and Gossner gives an upper limit of the density of electrons at 1 A.U. as 1000 cm^{-3}.

In view of Mie's theory of scattering, Siedentopf *et al* (1953) and Elsässer (1954) did not consider it possible for the dust particles to contribute materially to the polarized component of zodiacal light which they ascribed to scattering by electrons the brightness of zodiacal light was associated mainly with the scattering by dust particles. On this basis they deduced from photoelectric observations, the various densities of electrons and dust particles at different distances from the sun, the values being 600 cm^{-3} and 1.2×10^{-15} cm^{-3} respectively at 1 A.U. Generally the observations on the outer corona do not extend beyond 1° elongation from the sun, while those on the zodiacal light commence from 30° elongation, leaving a region between 1° to 30° elongations missing. But during the eclipse of February 25, 1952 at Khartoum, Pietenpol and Rense's (1953) observations covered the region between 5° and 15° elongations and confirmed that the zodiacal light is accounted for by the presence of a lenticular meteoric dust cloud having density falling off as r^{-1} (Jackson and Rense, 1953).

II

Of special interest to us are the variations of the intensity of the zodiacal light observed from time to time. The seasonal variations are well marked. There are other variations, which according to some observers (Elvey, 1937; Hulburt, 1930), occur during meteoric showers or geomagnetic disturbances. Hulburt (loc. cit) pointed out that no planetary theory could account for the rapid variations in the brightness of the zodiacal light during geomagnetic disturbances and hence suggested an atmospheric theory based on the action of the molecules and ions formed in the upper atmosphere of the earth by solar ultraviolet light. It appears to the present writer that some of the magnetic storms mentioned by Hulburt were M-storms having a 27-day recurrence tendency suggesting a relationship between the zodiacal light and the solar corpuscular streams responsible for the geomagnetic disturbances. In fact, Whipple and Gossner (loc. cit.) had hinted a possible contribution to the luminosity of the zodiacal light from the scattering of sunlight by a high concentration of free electrons in the solar corpuscular streams. In this paper an attempt has been made to explain the variations of the brightness of zodiacal light, from a consideration of the behaviour of the material responsible for the phenomenon.

III

Allen (1944, 1946) identified the solar corpuscular streams with the coronal streamers through which coronal matter is supposed to be forced out in the form of a jet, containing electrons and positive ions (mostly protons) in equal numbers so as to make the streamers neutral. The streamer becomes luminous as a result of the scattering of sunlight by the electrons in the streamer, the scattering due to protons being negligible. The visible portion of the streamer has been so far traced up to 12 solar radii. Hewish (1955) has located them up to 15 solar radii by their scattering effect on the radiation from the radio star Taurus. The extension of the streamers as far as the earth is supported by geomagnetic and auroral effects. As the longest coronal streamers have been found to originate from the equatorial regions of the sun, where the M-regions are also believed to exist, it may be assumed that the streamers which are responsible for the geomagnetic disturbances also originate from the equatorial regions of the sun.

We shall now consider the behaviour of two groups of corpuscles which are likely to affect the earth:

(i) Group I, having velocities greater than the 616 Km/sec., the velocity of escape from the surface of the sun. (For evidence of the presence of these corpuscles, see discussion by Sen Gupta and Mitra, 1954).

(ii) Group II, having velocities at the time of emission from the surface of the sun smaller than 616 Km/sec.

Group I. *Velocity of emission greater than* 616 *Km/sec.*

The corpuscles with these velocities describe parabolic orbits which at large distances make the emission appear almost radial. Chapman (1940) while considering the relationship between the fast corpuscles associated with solar flares and certain intense geomagnetic storms likened the corpuscular stream to a fire hose rotating with the sun. The stream overtakes the earth from the western side and causes the geomagnetic disturbances. The earth is found to be affected only when the solar flare occurs within 40° of the centre of the sun's disc.

The rotation of the sun enables the corpuscular stream to describe a volume having a section perpendicular to the ecliptic as given roughly by the broken

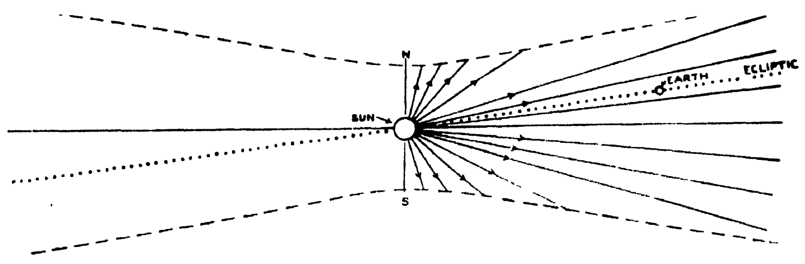

Fig. 1

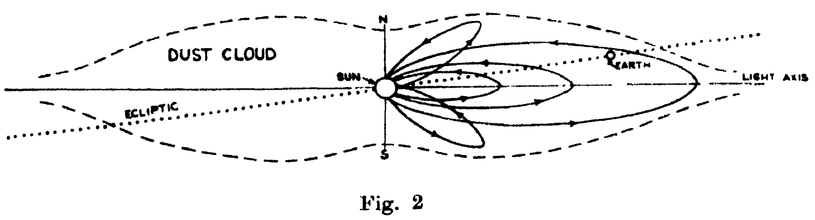

Fig. 2

lines in figure 1 (in which the depression at the centre represents diminished activity at the higher latitudes of the sun beyond 40°). A few interplanetary dust particles are likely to be swept with the corpuscular stream and will behave in a similar manner. However, the probability of encounters with dust particles will be extremely small and negligible, unless the stream density is sufficiently high. The volume in figure 1 contains mostly protons, electrons and a few interplanetary dust particles. As the corpuscular stream diverges like a jet, the density will fall as r^{-2}. Temperature diffusion may be neglected unless the temperature is of the order of 10^5 °K or more.

Group II. *Velocity of emission at the surface of the sun, smaller than* 616 *Km/sec.*

The emission of corpuscles having these velocities is likely to be a persistent feature even when the sun is quiet. The corpuscles describe Kepler orbits with the centre of force located in the sun's centre. It may be mentioned that Bredechin and Schaeberle (see van de Hulst, 1953) also believed such elliptical orbits to exist when they proposed a mechanical theory to explain the form of the streamers. The major and minor axes for a few cases are given in the following table in terms of R the radius of the sun. For comparison the sun-earth distance may be taken as equal to 200 R approximately.

TABLE I

Velocity Km/sec.	$2a$	$2b$
500.0	2.9	2.8
600.0	19.5	8.6
614.0	154.2	24.8
614.5	206.1	28.6
615.0	308.3	36.1

It is seen that when the velocities approach the velocity of escape from the sun, the orbits become highly elongated and extend beyond the ecliptic. As the long coronal streamers emerge from the equatorial regions of the sun, we may infer that the more elongated ellipses have their major axes nearly parallel to the plane of the ecliptic. The planes of these ellipses will, however, be slightly inclined to the plane of the ecliptic so that with the rotation of the sun these elliptical jets will describe a volume having a section given by the broken line in figure 2 normal to the plane of the ecliptic. Interplanetary dust particles caught in these corpuscular streams will have a tendency to concentrate within the volume. It may be mentioned that as the density of the corpuscles in these streams is not sufficiently high and the density of dust particles in interplanetary space is extremely small, the number of encounters will be very few and far between of the order of one in 10^5 years (Öpik, 1954). However, since the birth of the sun about 10^{12} years ago (Jeans, 1938), the number of encounters would be about 10^7. We may therefore regard the formation of the volume, as an evolution of the system with the solar system. It is suggested that the *zodiacal light is caused by the scattering of photospheric radiation by the electrons and dust particles within this volume*. Slower corpusceles associated with diminished solar activity at the higher latitudes would give rise to the depressed parts in the volume to the north and the south of the sun. Except for the depressions, which will not be noticeable from the earth the appearance of the volume is almost lenticular and accounts for the conical shape of the zodiacal light and its orientation along the plane of the ecliptic. The minor axes of the ellipses, with limiting values of the order of 30 *R* or so, determine the thickness of the lenticular cloud. Due to the inclination of the planes of the ellipses to the plane of the ecliptic, the thickness of the cloud in figure 2 is likely to be about half this value , that is, 15 *R* or about .08A.U. If we allow for the divergence of the jets, which constitute these orbits, at the boundaries the thickness of this cloud will be slightly greater and comparable with the estimate of van de Hulst (loc. cit). The dilution of electrons in the elliptical jet stream may be taken as proportional to $1/vr^2$, that is, the fall in density due to divergence will be partly compensated by the increase in density with diminishing velocity v towards the aphelion. If at the aphelion at 1 A.U. (is 200 *R*) of an elliptical stream, the density of electrons is taken as 600 cm^{-3}, the densities at the aphelions of smaller ellipses may be calculated and compared with those deduced by Behr and Siendentopf (1953) from photometric observations, as follows:

TABLE II

Distance from Sun	Density $\propto 1/vr^2$	Density as deduced by Behr and Siedentopf along the plane of the ecliptic
200 R	—	600 cm^{-3}
180 R	666 cm^{-3}	780 ,,
160 R	750 ,,	900 ,,
120 R	1000 ,,	1030 ,,
100 R	1200 ,,	1070 ,,

According to the second column, the density is found to vary as r^{-1}. A further fall in density due to temperature diffusion may be neglected as in the case of Group I of the corpuscles. It has already been stated that the most elongated ellipses extend along the sun's equatorial plane. From qualitative considerations the smaller ellipses, with axes inclined to the sun's equatorial plane may be taken to be confined within the dotted line. Hence the densities given in column 2 above will be found to occur in spherical shells having the respective radii given in column 1 of Table 2 and limited by the dotted line of figure 2. However, due to the preponderance of largest number of elliptical streamers with their major axes almost parallel to the sun's equatorial plane, there will be a tendency for the density of electrons to be highest near the sun's equatorial plane diminishing towards the north and south. According to Elsässer (loc. cit.) the electrons are distributed in ellipsoidal shells with the axis of rotation passing through the sun's centre perpendicular to the plane of the ecliptic.

In the present treatment, the density distribution of the dust particles is supposed to be subject to encounters with the electrons and positive ions of the solar corpuscular stream. With every impact, the dust particles swept towards the earth will accumulate towards the aphelion with the result that there is a piling up of the dust particles in the vicinity of the earth. The above consideration also shows that we need not take into account much higher velocities of Group II, as the dilution of electrons in the stream associated with the highly elongated orbits may be too great to enable the scattered light to contribute materially to the luminosity. The transit from the aphelion back to the sun brings about a reversal of the above process. The stream converges and the density of the electrons increases until the sun is reached. However, due to the increasing velocities of the stream, the density of the dust particles swept with it, may first diminish, and thereafter increases towards the perihelion. *In this manner the interplanetary dust particles may be carried with the solar corpuscular stream into the sun, and provide at least partially, the energy, which causes the high temperature of the corona.* In the immediate vicinity of the sun, within a distance of about 0.1 A.U. the space is devoid of dust particles which are vaporized by the high temperature of the sun (van de Hulst, loc. cit.).

Unlike the fast corpuscles of Group I, which cover the distance from the sun to the earth in 1 to 4 days (Sen Gupta and Mitra, loc. cit.), the slow corpuscles of the Group II would take several weeks in transit to cover the same distance. It has already been suggested that the evolution of the volume in figure 2 containing Group II corpuscles (electrons) and interplanetary dust particles account for the unvarying shape of the zodiacal light. The effect of Group I corpuscles due to solar flares and M-region activity is superimposed on the above augmenting the number of free electrons in the volume (figure. 2), with the result that the zodiacal light becomes brighter at the same time when geomagnetic disturbances occur. In a similar manner the advent of meteor swarms in the interplanetary space augments the number of dust particles and thereby brings about an intensification of the zodiacal light. Figure 2 represents conditions on September 5 when the earth has the highest heliographic latitude 7.3°. As may be seen from figure 2, the light axis of the phenomenon, which may be taken to coincide with the sun's equatorial plane, is inclined at this time about 7.3° to the south of the ecliptic plane.

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